ADVANCED CHEMICAL HYDRIDE-BASED FUEL CELL SYSTEMS FOR PORTABLE MILITARY APPLICATIONS

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ABSTRACT

The modern military continues to introduce advanced electronic devices such as night vision equipment, global positioning systems, laser range finders and target designators, digital communications systems, remote networking and intelligence gathering sensors. These new technologies are generating ever-increasing power requirements for the modern soldier, and today's state-of-the-art batteries and other traditional power generation sources are failing to keep pace with these growing power needs.

New technologies are emerging as possible solutions to this problem, with fuel cell technology considered the most promising. Hydrogen fuel cells are of particular interest due to low temperature operation, prompt cold start-up and relative technology readiness, among other benefits. Paired with silent, reliable hydrogen fuel cell power systems, chemical hydrides can provide very high energy density for use in demanding portable applications. Sodium borohydride, which is currently employed in Protonex systems, is also non-toxic, non-flammable, and cost-effective. These integrated systems are well-suited for military applications, as they are able to meet demanding performance targets such as ultra-low weight, wide operating temperature range, and low heat and noise profiles.

Programs currently underway at Protonex, a leading provider of fuel cell systems for portable applications, are focused on developing fully integrated power solutions at 30 watts (for man-portable soldier power) and 250 watts (for unmanned aerial vehicles). These products feature sodium borohydride fueling subsystems that provide a continuous supply of hydrogen as the system requires.

1. INTRODUCTION

Lightweight, compact power sources are of critical need to a broad range of defense, homeland security and communication applications. Many hydrogen proton exchange membrane (PEM) fuel cell systems are reaching reliability and performance targets that make them ready for field trials. However, hydrogen storage, generation, transportation and purity issues have been major concerns. The DoD's recent shift in focus from the 'cell to fuel' underscores the need for development of energy-dense portable hydrogen storage and generation systems to fuel these fuel cells. New methods of on-demand pure hydrogen generation are being developed, and chemical hydrides have emerged as a solution that is gravimetrically high in extractable hydrogen content and can provide safe, quiet, lightweight solutions to meet the escalating energy demands of portable applications.

Protonex has worked with its strategic partner Millennium Cell to develop advanced fueling subsystems based on sodium borohydride. This substance is safe, energy-dense, reliable and cost-effective.

PEM fuel cell systems integrated with sodium borohydride fueling subsystems are able to meet the aggressive performance targets of the military, such as operating temperature and heat and noise profiles.

1.1 Fuel Cell Technology

A fuel cell is a device that uses hydrogen from a fuel source and oxygen from the air to cleanly and efficiently produce electricity using an electrochemical process. Proton exchange membrane (PEM) or hydrogen fuel cell technology is the most advanced and most promising for many applications due to its low-temperature operation, quick start-up and demonstrated longevity. PEM systems are also generally smaller and lighter than same-power-output systems based on competing technologies.

The core of a fuel cell system is the fuel cell stack, which is created by stacking bipolar plates (with reactant flow fields) next to membrane electrode assemblies that consist of an electrolyte (membrane) and two catalyst-coated electrodes (a porous anode and cathode). Fuel cell systems also contain a number of pumps, valves, electronics and other specialty components ("balance of plant") that make up the rest of the system, including fuel supply, cooling and power management.

1.2 Background

Protonex' hydrogen fuel cell systems offer advantages over comparable fuel cell systems because they are based on fuel cell stacks that are designed and manufactured according to a patented injection molding technology. This technology yields stacks (Figure 1) with

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high power densities, reduces the number of parts and labor required, and makes the overall system much more reliable. With this innovation, Protonex is able to volume produce reliable, high-performance fuel cell stacks at low costs. These stacks have demonstrated more than 4000 hours of operational life and require very little active control when incorporated into a fuel cell system, which allows them to be integrated with inexpensive, commercially available and proven balance of plant components.

Figure 1: Protonex fuel cell stacks (30 to 500 watts)

2. SOLIDER POWER

Protonex' 30- to 50-watt soldier power system is based on an innovative fueling design that features a snap-in, 24-hour chemical hydride fueling cartridge for prolonged mission length, maximum flexibility and high energy density. The first-generation prototype (P1) was delivered to the Department of Defense in 2005 for initial field testing. This system was independently tested to have an energy density of 380 watt-hours per kilogram and provide a 60% weight savings over the incumbent battery solution.

The second-generation prototype (P2 - Figure 2), which offers better performance metrics, including an operating temperature range from -20^{o}C to 50^{o}C, increased ruggedness, reliability and usability, is in small-scale production and became available in the spring of 2006 to select military customers for field trials. Work on the soldier power platform was funded and supported by the U.S. Air Force and U.S. Army.

2.1 Fueling

The P2 system uses a replaceable sodium borohydride fuel cartridge (Figure 3) to provide 30 watts of nominal continuous power with the ability to peak to more than 100 watts (via integrated battery). remanufactured or disposed of after use. The system is compact and lightweight—much more so than the primary lithium batteries soldiers currently carry to provide portable power.

Figure 2: Protonex P2 Soldier Power System

Figure 3: Protonex P2 system showing fuel cell (left) and cartridge (right) components

2.2 Benefit to the Warfighter

Each cartridge lasts for 24 hours at 30 watts, and can be For a typical three-day, 30-watt mission, a soldier will carry 13 BA5590 batteries—a total of 29.3 pounds and 11.2 liters in volume. The Protonex P2 can provide the same energy at only 11.2 pounds and 5.6 liters. This huge savings allows the soldier to carry additional supplies or protective equipment that would have to be left behind with use of batteries. The P2 system is also expected to generate significant cost savings for the military over the lifecycle of the unit.

Because the P2 fuel cell system weighs less than a kilogram and, with similarly lightweight fuel cartridges, provides long-duration power, the energy density of the system is quite high. To drive metrics higher, the chemical hydride fuel cartridges can be shipped dry—without the water portion of the fuel solution. The water can then be injected into the cartridges as needed in the field. This saves about two-thirds of the cartridge weight (.52 kilogram versus 1.38 kilograms [1.15 pounds versus 3.04 pounds]). In this case, with water only added in the field when needed, the energy metric doubles to 860 watt-hours per kilogram. With a fully hydrated cartridge, P2 has an energy density of 425 watt-hours per kilogram. With further development of the power system using

advanced chemical hydrides, Protonex expects the energy density of its soldier power system to reach over 1,000 watt-hours per kilogram.

BA5590 Batteries	
Units required:	**13**
Total weight:	**29.3 lbs**
Total volume:	**11.2 liters**
Cost/mission:	**$1,040**

Protonex Fuel Cell System	
Units required:	**1 system**
	3 cartridges
Total weight:	**7.9 lbs**
Total volume:	**4.3 liters**
Cost/mission:	**$800**

Figure 4: Comparison of BA5590 military batteries and P2 fuel cell solution for 3-day, 30-watt mission

3. UNMANNED AERIAL VEHICLE PROPULSION

In addition to solider power, Protonex has identified small tactical unmanned aerial vehicles (UAV) as an application that can realize immediate benefits from fuel cell technology. Demands for broader mission capabilities have increased due to rapid growth in the segment of military and commercial UAVs designed for surveillance, chemical-biological monitoring, border patrol and other specialty missions. While batteries are an ideal power source for 1 to 2 hour flights times, powering UAVs for prolonged missions has been a formidable technical challenge.

Fuel cells have emerged as a promising next-generation power source for the man-portable/backpackable class of UAV because they offer higher specific energy than lithium polymer batteries currently used to power long-duration UAVs. They are highly efficient, compact and lightweight. In addition, fuel cells offer a quiet and reliable alternative to the noise and unpredictability of combustion engines, which are also often used to power long-duration aircraft. With fuel cell power systems, small UAVs are expected to achieve flight times as long as 12 hours. This capability has the potential to enable an entirely new class of UAV applications that currently do not exist because required power sources are not available. Unmanned ground vehicles with similar needs for long-duration missions are also expected to realize new possibilities with fuel cell technology.

The power range for this technology approximately ranges from 50 watts during cruise to 500+ watts during takeoff and climbing. For vehicles requiring less than 50 watts, possibilities exist for fuel cell technology to offer benefits, but the current fuel cell technology in development at Protonex is likely not applicable to vehicles under 50 watts due to certain requirements of the fuel cells. For vehicles drawing more than 500 watts, engines are a good power source because at that power output, engines have fairly high reliability and high specific power to enable longer endurance missions.

3.1 Applications

UAV fuel cell power systems will likely be used by the U.S. military first for small, backpackable UAVs with extended flight duration capability for persistent surveillance, monitoring of convoy lines and perimeters, search and rescue and chemical-biological monitoring. However, several classes of extended flight duration craft are used by all branches of the U.S. military and, as power requirements continue to increase across these sectors, may represent a secondary market for fuel cell power. There are also a large number of non-military applications and unmanned ground system applications which have similar requirements for long-duration missions and may benefit from fuel cell technology.

3.2 Benefits

To develop fuel cell power sources with high specific energy, thereby enabling longer UAV missions, three areas of technical importance need to be maximized. These three areas are: specific power of the fuel cell system (watts per kilogram), specific energy of the packaged fuel cartridge (percent by weight hydrogen), and the conversion efficiency at which the fuel cell system converts the hydrogen to electricity. Specific power determines the amount of payload a plane can carry, its flight speed and lift to drag ratio. High specific energy enables increased flight duration.

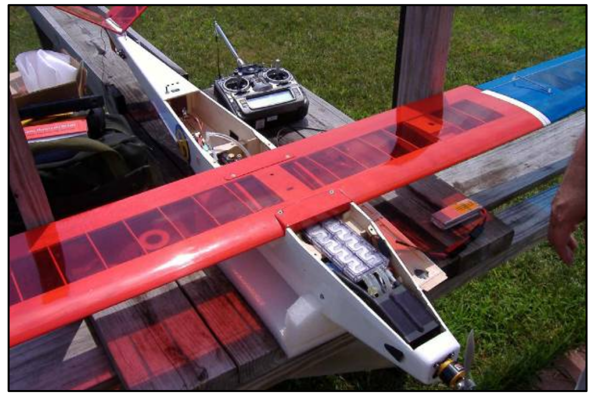
The greatest advantage fuel cells bring to the UAV application is an increase in specific energy of the electrical power source compared to batteries, allowing increased flight duration. When designing a fuel cell system for an aircraft, both the specific power and specific energy requirements must be met to provide the needed flight capabilities and mission duration respectively.

3.3 Achievements to Date

Protonex is working with the Naval Research Laboratory (NRL) and Air Force Research Laboratory (AFRL) to demonstrate the high specific energy capabilities of fuel cell systems as a quiet electrical propulsion source for small, backpackable, long-endurance UAVs. To date, the NRL has completed two test flights using Protonex fuel cell technology, and Protonex has been awarded two contracts by the AFRL for UAV power system development.

The first test flight was conducted by the NRL in July 2005 using half a tank of compressed hydrogen as the fuel source. The NRL's 5.6-pound "Spider Lion" UAV (Figure 5) flew for 1 hour 43 minutes before the tank ran out of hydrogen. In November 2005, the NRL conducted a second test flight of the Spider Lion using a full tank of compressed hydrogen. The UAV flew for 3 hours 19 minutes including climbing and maneuvering after being released in-flight from another larger UAV. The test flight was took place at L-3 BAI Aerosystem's Ragged Island Flight Operations facility in Maryland.

The fuel cell power system tested was designed around a Protonex fuel cell stack capable of producing 87 watts at 12 volts, and 130 watts peak at 9 volts. This stack was chosen based on calculated power requirement of 80 to 100 watts for steady flight. A custom fuselage was built to accommodate the fuel tank, fuel cell and supporting equipment (mostly commercial hardware). The Spider Lion's second flight also ended because the hydrogen tank was empty. New developments at Protonex and optimization of the fueling solution will at least double the stored available energy, allowing flight times of at least 6 hours (depending on the aircraft).



Figures 5: NRL's Spider Lion UAV powered by Protonex fuel cell system

Protonex was first awarded a contract with the AFRL for development of a UAV power system in October 2005. Under this program, Protonex advanced the specific power of its fuel cell system to 150 watts per kilogram. The system will eventually be hybridized with a battery for 350+ watts of additional peaking power.

A chemical hydride-based fueling solution for the system was also advanced under the program. The main challenge with any chemical source of hydrogen is extraction of the largest possible percentage by weight of hydrogen from the source. Under the initial AFRL program, Protonex improved this capability from 2.88% to approximately 4% by weight hydrogen, significantly improving the overall efficiency of the system.

Success in this first AFRL program resulted in award of a follow-on contract, which began in July 2006 and is currently underway at Protonex.

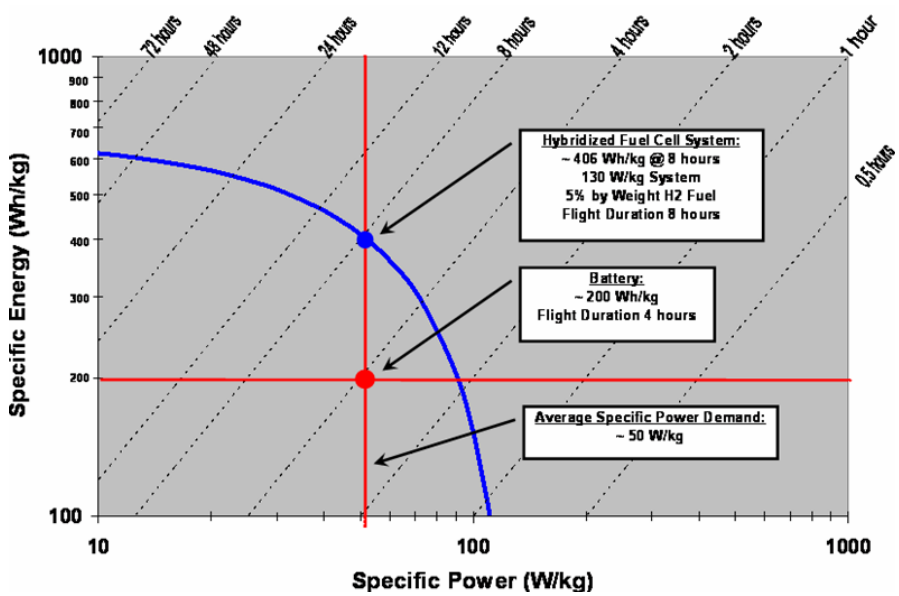


Figure 6: Ragone plot of fuel cell system and battery

The current program is focused on integrating the improved fueling solution with a 50% electrically efficient PEM fuel cell system. This combined electrical power source will have an energy density greater than 500 watt-hours per kilogram, which will enable 6 to 12 hour UAV missions. This energy density is more than twice that of the state-of-the art lithium batteries used in electrical UAVs, which currently achieve approximately 200 watt-hours per kilogram and are projected to reach a maximum of approximately 300 watt-hours per kilogram in five years.

Potential advancement of PEM fuel cell-based power systems is shown on a Ragone plot (Figure 6). This plot shows the power/energy domain of lithium battery technology, the lower line bounded by a specific energy of 200 watt-hours per kilogram and a specific power of 50 watts per kilogram. The blue curve highlights advancements of the Protonex UAV fuel cell system. The curve also shows potential advancement by switching from compressed hydrogen as the fuel source to the chemical hydride system currently under development. It is these two factors, the specific power of the fuel cell system and the specific energy of the advanced fueling solution, which will enable the integrated solution to achieve specific energy densities well in excess of 500 watt-hours per kilogram. Ultimately, fuel cell-battery hybrid systems are expected to provide the best power solution for UAVs. High discharge rate batteries can provide the surge power need during takeoff and maneuvering while the fuel cell system can provide base load for flat float and battery charging power.

3.4 Current Activities

As Protonex continues to advance its high power fuel cell system and high energy fuel cartridge technologies under the AFRL program, it is also focused on integration of the complete power system into a UAV platform. Protonex is working closely with UAV manufacturers to design its UAV power system specifically for integration into small UAV platforms.

Current fuel cell stack technology at Protonex is approaching specific power of 1,000 watts per kilogram, enabling power systems with even higher performance specifications. Table 1 lists the specifications of the latest fuel cell power system developed for a backpackable UAV. This power source improvement will broaden the mission capabilities for small UAVs, significantly extend flight times and allow aircraft to carry greater payload.

Table 1: Specifications for Protonex UAV Propulsion System

System	Net Output Power	50-200 Watts
	Output Voltage	20-30 Volts
	Output Current	1-10 Amps
	Nominal Endurance	6-12 Hours*
Fuel	Composition	Sodium Borohydride
	Available Energy per Cartridge	770 Wh
Physical	Fuel Cell System Weight	700 grams
	Fuel Cartridge Weight	1300 grams
	Power System Weight	2000 grams
	Power System Volume	70.8 in^3 (2799 cm^3)
Emissions	Hydrogen	36 sccm
	Water	0.5 sccm
Noise	MIL-STD-1474D	Level 1 Aural Nondetectability at 300m
Environment	Ambient Temperature	-10^{o}C - 50^{o}C
	Relative humidity	0% - 95%

* Depends on aircraft. Specifications subject to change.

4. SODIUM BOROHYDRIDE METRICS

As Table 2 and Figure 8 illustrate, sodium borohydride-based power sources offer energy density metrics that are superior not only to traditional battery solutions, but also to current direct methanol fueling solutions. Even the most advanced zinc-air batteries (such as the military BA8180) are eclipsed.

Table 2: Comparison of Battery and Chemical Hydride Energy Density

Power Source	Whr/kg	
Lithium Primary (BA5590)	150	
Lithium Rechargeable	130	
Zn-Air (BA8180) – limited current	260	
Protonex Chemical Hydride Gen I (H104)	**380**	**DRY – Whr/kg**
Protonex Chemical Hydride Gen II (05/06)	**425 - 500**	**860 - 935**
Protonex Chemical Hydride Gen III (06/07)	**500 - 1000$^+$**	

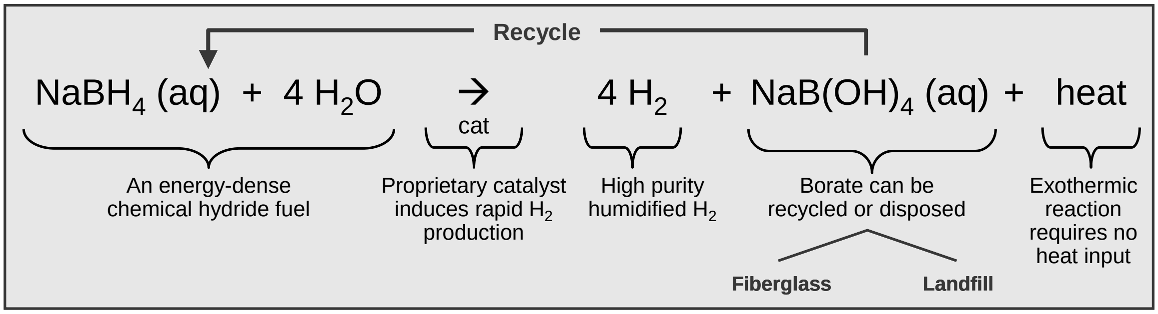


Figure 7: Sodium borohydride hydrogen extraction process

Compared to methanol solutions, using just the calculated energy density of the two fuels, sodium borohydride surpasses methanol in terms of specific energy at 100 weight percent concentration by more than 1,000 watt-hours per kilogram. This, paired with the greater efficiency of PEM fuel cells (50% versus 20-30% for direct methanol), allows complete PEM/sodium borohydride systems to achieve fuel energy density of at least 1,500 watt-hours per kilogram more than direct methanol systems. In addition, sodium borohydride fuel is non-flammable and can be stored at ambient pressure and temperature. Hydrogen generation can be controlled to deliver broad ranges of power, energy, and pressure, and requires relatively low reaction temperature (<<100°C).

4.1 Field Hydration

Another benefit of sodium borohydride-based systems over other power sources is the ability to save weight by hydrating in the field. As earlier discussed, the Protonex fuel cartridges for the P2 system may be injected with water in the field to create the solution needed to generate hydrogen, saving .86 kilogram (1.9 pounds) per cartridge. For a three-day, 30-watt mission, this would total 2.5 kilograms of saved weight, added to the initial weight savings of using the fuel cell solution rather than batteries.

A series of tests were performed by Millennium Cell to understand the effects on system performance of using other water-based liquids, including brackish water and synthetic urine.

Hydration with Brackish Water: As shown in Figure 9, hydrating the fuel cartridge with brackish water had very little effect on the performance of the system. Data were taken on fuels made from DI water and brackish water at high hydrogen flow rates. Initial data indicate no measurable effect on performance or hydrogen purity.

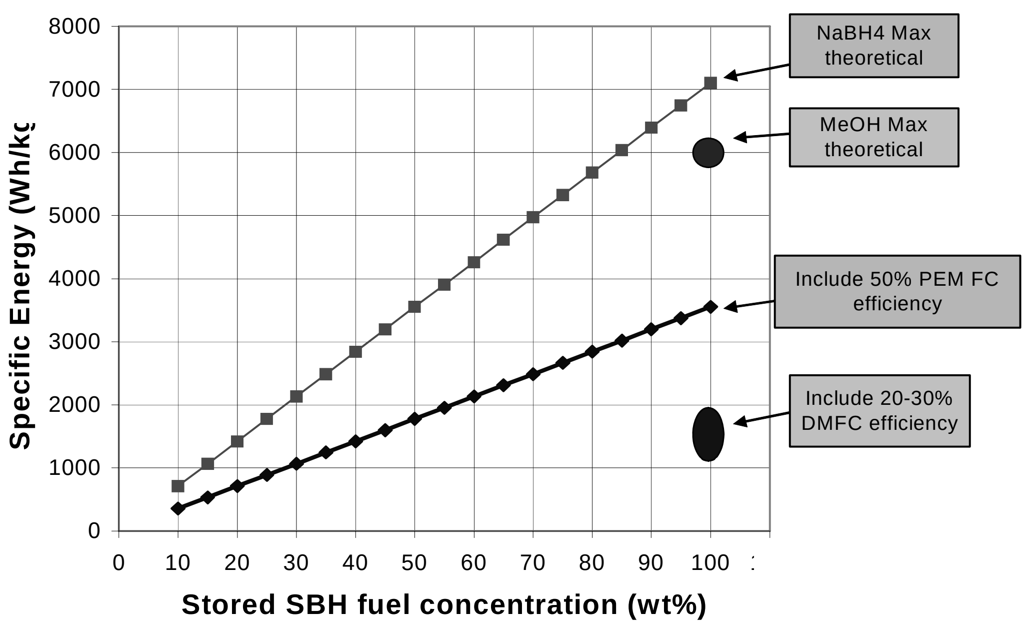


Figure 8. Calculated fuel only energy density
(courtesy of Millennium Cell)

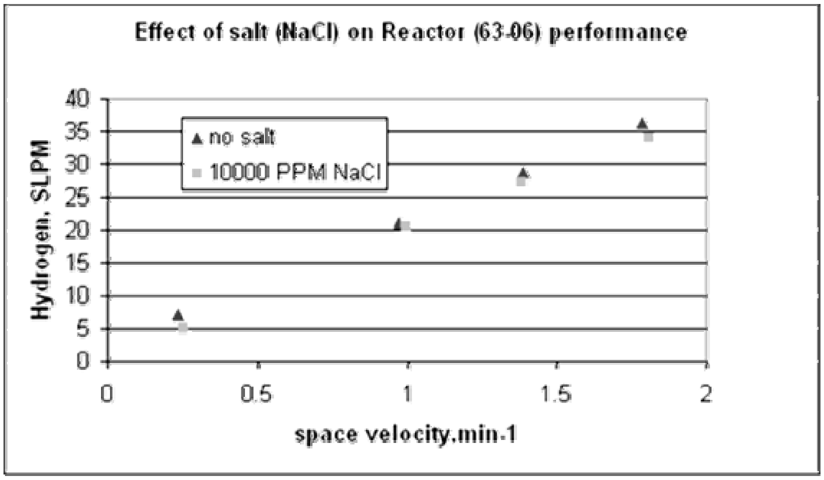


Figure 9. Results of hydration test with brackish water
(courtesy of Millennium Cell)

Hydration with Synthetic Urine: As shown in Figure 10, hydrogen was also able to be generated successfully during tests with unpurified, unfiltered synthetic urine. Some catalyst degradation occurred due to organic impurities, which was expected. This would not have an adverse effect on the overall system performance, however, because each fuel cartridge is used for only 24 hours, at which point it is discarded or returned for remanufacture. This allows the cartridge to employ a very simple, inexpensive catalyst (enabling low cartridge cost) and allows even accelerated breakdown of the catalyst to have negligible effects on power output. In an emergency situation, when no water is available, urine may be used to hydrate the cartridge to generate power for a remarkably long period of time. Simple filtering expected to be sufficient to ensure hydrogen generation for the lifetime of a cartridge (24 hours).

Hydration with Other Liquids: Programs are in place at Millennium Cell to study multiple water sources and purification technologies for field hydration. Fuels made from tap water have also been tested with negligible effect on catalyst performance, and it is expected that most water-based fuels will allow hydrogen generation at full power.

4.2 Transport of Sodium Borohydride

Sodium borohydride is non-toxic and non-flammable, and able to be transported by standard means. It offers several advantages over primary lithium batteries and other fuels. Cnsidered a Class 8 corrosive material, it may be air-shipped in small quantities via passenger air/rail. Lithium batteries are considered Class 9 miscellaneous hazardous materials, and are forbidden even as cargo on passenger air/rail. Methanol is a Class 3 flammable liquid.

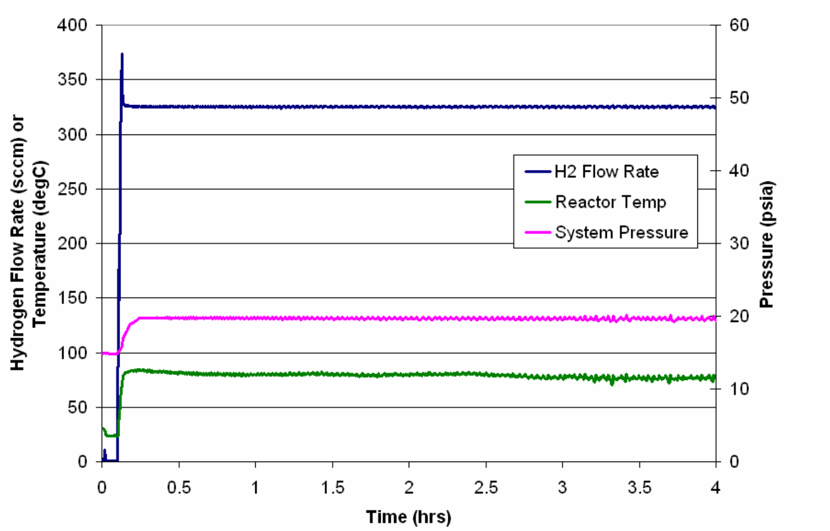


Figure 10: Results of hydration test with synthetic urine
(courtesy of Millennium Cell)

5. THE PATH TO PRODUCTION

Fuel cells offer many benefits to the modern warfighter. The applications that Protonex has identified as areas where they may offer the greatest and most immediate benefit are backpackable soldier power for powering the myriad of equipment carried by soldiers in the field and long-duration tactical UAVs. While fuel cell system and fueling technologies are advancing, two major tasks remain before these advanced power solutions can be most effectively realized and delivered in volume to the warfighter. First, the power system must be integrated into the application platform. For solider power, this means hybridization with current battery technology (to offer battery charging and peaking capabilities) via a custom power manager. For UAVs, the fuel cell system will need to be fully integration into an air frame to reduce the overall volume and weight of the power system, further improving power and energy metrics. Once integration is complete in these applications, the full system will require additional refinement based on in-the-field studies to tailor the mode of use for a specific mission scenario (i.e. specific equipment and/or environmental conditions, etc.). This will include both a design refinement stage, as well as the transition to a manufactured product.

Fuel cell technology will enable greater capability across all of these applications, strengthening military and security operations. Progress to date has shown that fuel cell power sources that can surpass today’s most advanced battery technology in terms of energy density, with comparable reliability, are well within reach, opening new doors to future warfighter applications.